Processes with light ions

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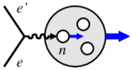
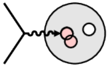
in collaboration w C. Weiss
JLab LDRD on spectator tagging
(non-exhaustive)

Supported by

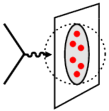
Ions: physics objectives



- **Neutron** structure
  - flavor decomposition of quark PDFs/GPDs/TMDs
  - flavor structure of the nucleon sea
  - singlet vs non-singlet QCD evolution, leading/higher-twist effects

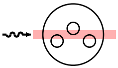


- Nuclear **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - non-nucleonic components
  - nuclear gluons



- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei

    → talk Hyde



- **Coherence** and saturation
  - interaction of high-energy probe with coherent quark-gluon fields

      → talks Kovchegov, Schenke, Venugopalan

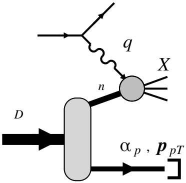
Nuclear structure: A tale with two sides

- Low-energy nuclear structure enters as **input** in a whole range of calculations for EIC
  - But high-energy nuclear scattering
    $\rightarrow$ light-front quantization

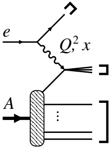
- **Novel studies** of nuclear structure at EIC
  - Short-range correlations
  - Non-nucleonic components
  - Breakup, Final-state interactions

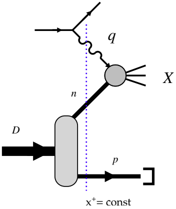
EIC: unique opportunities

- Detection of nuclear breakup (spectator tagging) / coherent scattering
  - Enabled by the EIC far-forward detectors / secondary focus
  - Additional **control** over initial configuration
    - $\leftrightarrow$ averaging over all configs in inclusive scattering
    - $\rightarrow$ on-shell extrapolation [Sargsian, Strikman '05; WC, Weiss 19+]
    - $\rightarrow$ differential study of medium modifications
    - $\rightarrow$ needs modelling of **final-state interactions**



- Light ions
  - $\rightarrow$ polarization; different spins d, ^{3}H(e), ^{4}He
  - $\rightarrow$ precision predictions with ab initio wave functions
- Lots of potential for **novel measurements**
  - $\leftrightarrow$ more challenging in fixed target
- But needs **much more theory input**!





- Interplay of two scales: high-energy scattering and low-energy nuclear structure. Virtual photon probes nucleus at fixed lightcone time $x^+ = x^0 + x^3$
- Scales can be separated using methods of light-front quantization and QCD factorization
- Tools for high-energy scattering known from *ep*
- Nuclear input: light-front momentum densities, spectral functions, overlaps with specific final states in breakup/tagging reactions
  - framework known for deuteron,
can be extended to few-body $A > 2$ but challenges
  - still **low-energy** nuclear physics, just formulated differently
- Structure functions (IA) $F_A \propto F_N(\tilde{x}, Q^2) S(\alpha_p, p_{pT})$

Light-front nuclear structure

- LF gives rise to
  - Relativistic spin effects
  - Dynamical variables in LF boosted rest frame of on-shell A-nucleon state
- We currently match to the NR (ab initio) wf for light nuclei
  - Ab initio / EFT based methods could be extended to light-front quantization
  - Mean-field formulation for medium/heavy nuclei exist [Blunden, Burkardt, Miller 99]
- For $A > 2$ Poincaré invariance and cluster separability imposes non-trivial constraints [Sokolov 70s, Lev et al 90s]
  - Formalism is known [Sokolov packing operators], but technical
  - Trivial for deuteron
  - Applications to ^{3}He [Rinaldi,Pace,Salme,Scopetta et al]

Opportunity to involve the **low-energy community** in EIC physics

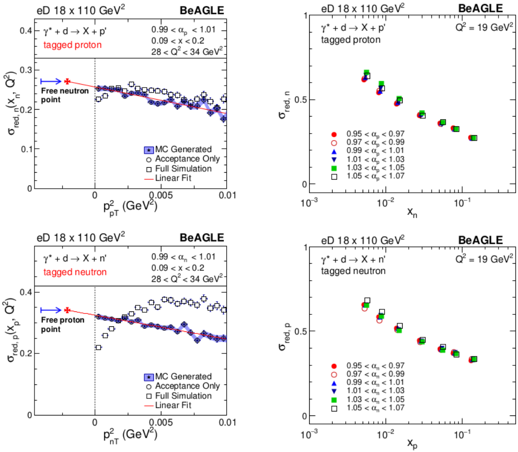
Reaction Frameworks

- Tagged spectator reactions
  - focused on DIS on deuteron
  - more complicated reactions (SIDIS, incoherent exclusive) possible
  - A>2, but FSI a lot more complicated
- (untagged) (SI)DIS on ^{3}He [Rinaldi,Pace,Salme,Scopetta et al]
- Coherent/incoherent DVCS on ^{4}He

  [Guzey et al; Liuti, Taneja; Perugia/Orsay: Fucini, Scopetta et al.;...]
- **Polarized deuteron** yields additional tensor polarized structure functions/observables $\rightarrow$ spin-orbit, FSI
- Polarized FSI

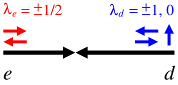
On-shell extrapolation of F_{2N}

$$F_{2d} = [2(2\pi)^3]\, S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{unpol}]\, F_{2n}(\tilde{x}, Q^2)$$



Detailed simulations for EIC [Jentsch,Tu,Weiss, PRC 21]

Polarized structure function g_{1n}: longitudinal asymmetry



- Pole extrapolation of double spin asymmetry
  - Nominator
    $d\sigma_{||} \equiv \frac{1}{4}\left[\mathrm{d}\sigma(+\frac{1}{2},+1) - \mathrm{d}\sigma(-\frac{1}{2},+1) - \mathrm{d}\sigma(+\frac{1}{2},-1) + \mathrm{d}\sigma(-\frac{1}{2},-1)\right]$
  - Denominators: 2-state

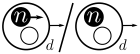
$$d\sigma_2 \equiv \frac{1}{4}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1)\right]$$

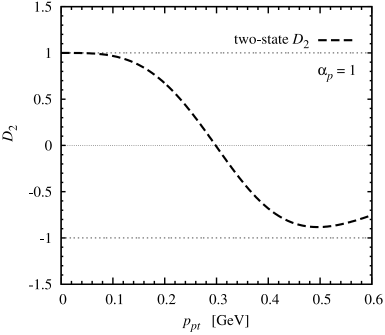
  - $\lambda_d = 0$ state **not needed**!
- Impulse approximation yields in the Bjorken limit $[\alpha_p = \frac{2p_p^+}{p_d^+}]$

$$A_{||,2} = \frac{d\sigma_{||}}{d\sigma_2}[\phi_h \,\mathrm{avg}] \approx \mathcal{D}_i(\alpha_p, |p_{pT}|)A_{||n} = \mathcal{D}_2(\alpha_p, |p_{pT}|)\frac{D_{||}g_{1n}(\tilde{x}, Q^2)}{2(1+\epsilon R_n)F_{1n}(\tilde{x}, Q^2)}$$

Nuclear structure factor $\mathcal{D}_2$

- Quantifies **neutron depolarization** due to nuclear structure
- Depends on spectator kinematics α_p, p_{pT}
- $\mathcal{D}_2 = \Delta S_d[\text{pure } +1]/S_d[\text{pure } +1]$ has **probabilistic interpretation**





WC, C. Weiss, PLB ('19); PRC ('20)

- Bounds: $-1 \leq \mathcal{D}_2 \leq 1$
- Due to lack of OAM $\mathcal{D}_2 \equiv 1$ for $p_T = 0$
- Clear contribution from D-wave at finite recoil momenta
- $\mathcal{D}_2$ close to unity at small recoil momenta
  $\rightarrow$ relevant for on-shell extrapolation

Tensor polarized observable A_{zz} [Frankfurt, Strikman '83]

- Analogue of $A_{LL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$ for vector polarization ($\sim S_L$) is the tensor asymmetry

$$A_{zz} = \frac{\sigma^+ + \sigma^- - 2\sigma^0}{\sigma^+ + \sigma^- + \sigma^0} [\phi_h \,\text{avg}]$$

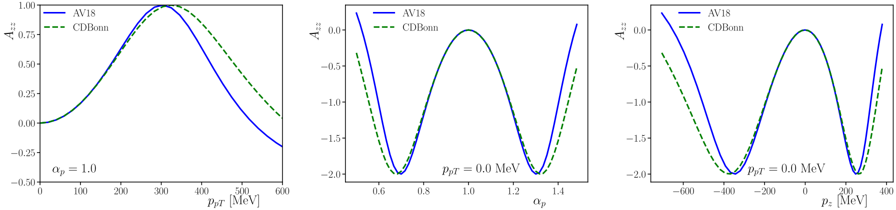
$\rightarrow$ **no** electron polarization required.

- Requires all three polarization states; $A_{zz} \in [-2, 1]$ and $\sim T_{LL}$
- $e\vec{d}$: A_{zz} measured in different ranges of Bjorken $x = 2\,\frac{Q^2}{2(p_d q)}$, $x \in [0, 2]$:
  - elastic $x = 2$ ["T_{20}"]: NIKHEF ('98), ...
  - quasi-elastic $x > 1$: NIKHEF ('99), BLAST @ MIT-Bates ('17), future JLab12
  - DIS inclusive $x < 1$ ["b_1"]: HERMES @ DESY ('05), future JLab12
    $\rightarrow$ HERMES measured very **small** values

Maximize A_{zz} with spectator tagging

- Tensor polarization is sensitive to unpolarized quark distributions, partonic factor cancels out → **ratio of LF densities** remains

$$A_{zz}(\alpha_p, \boldsymbol{p}_T) = -\frac{\frac{f_0(k) f_2(k)}{\sqrt{2}} + \frac{f_2^2(k)}{4}}{f_0^2(k) + f_2^2(k)} (3\cos 2\theta_k + 1) \qquad \alpha_p = \frac{2p_p^+}{p_D^+} = \left(1 + \frac{k^3}{\sqrt{m^2+k^2}}\right); \quad \boldsymbol{p}_{pT} = \boldsymbol{k}_T$$

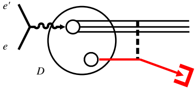


- Maximal A_{zz} at $f_2(k) = \sqrt{2} f_0(k)$, not the S wave node!
- $A_{zz} = 1$ at $\alpha_p = 1$ ($\theta_k = \pi/2$) → pure $m = \pm 1$)
  $A_{zz} = -2$ at $p_{pT} = 0$ ($\theta_k = 0, \pi$) → pure $m = 0$

→ **Constraints on deuteron D-wave**

FSI in DIS: physical pictures

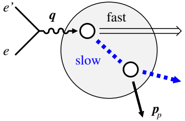
FSI can be min/maximized depending on spectator kinematics



subasymptotic regime:
low Q^2, high x

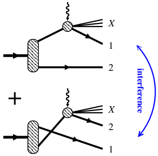
- rescattering of resonance-like structure with spectator nucleon in eikonal approximation [Deeps,BONuS].

`WC,M. Sargsian arXiv:1704.06117`



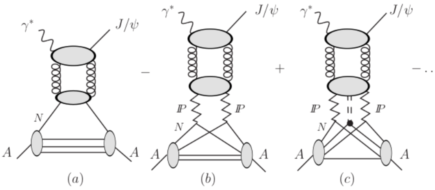
DIS regime, intermediate x

- FSI between slow hadrons from the DIS products and spectator nucleon, fast hadrons hadronize after leaving the nucleus.



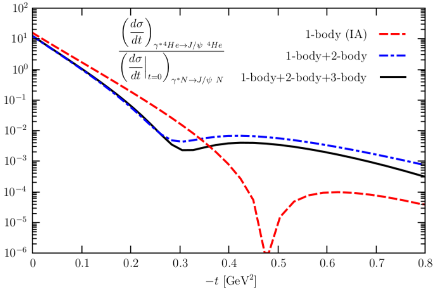
- Shadowing in DIS $x \ll 10^{-1}$
- For decreasing x the FSI become more and more low-energy NN scattering

Leading twist nuclear shadowing



Guzey, Rinaldi et al. 2202.12200

^{4}He coherent J/Ψ production



- Can be studied on heavy and light nuclei, large effect
- Gluonic imaging of nuclei $g_A(x, Q^2)$
- Likely gluons belong to more than 1 nucleon
- Shadowing one nucleon at a time in diffractive J/ψ production on light nuclei
- k-body FF enter in amplitude $\rightarrow$ nuclear wf

Conclusions

- Light ions address many aspects of EIC physics program
- Nuclear physics plays an important role
- Nuclear breakup and coherent scattering enable novel measurements
- Requires lots of theory input
- Several channels, aspects require work
- Complementarity with second detector